

PATENT
PDNO 200207084-1

PROGRAMMABLE WEAK WRITE TEST MODE (PWWTM)
BIAS GENERATION HAVING LOGIC HIGH OUTPUT DEFAULT MODE

INVENTORS:

JOHN WUU
1807 Jamison Court
Fort Collins, CO 80528

BLAINE STACKHOUSE
7854 Handy Court
Fort Collins, CO 80525

DONALD R. WEISS
7951 Mockingbird Drive
Fort Collins, CO 80525

PROGRAMMABLE WEAK WRITE TEST MODE (PWWTM)
BIAS GENERATION HAVING LOGIC HIGH OUTPUT DEFAULT MODE

TECHNICAL FIELD

The invention relates to integrated circuits (IC). In particular, the invention
5 relates to built-in self-test (BIST) used with static random access memory (SRAM).

BACKGROUND OF THE INVENTION

Among the typical tests that are performed on SRAM arrays are tests for
memory cell data retention faults (DRFs) and memory cell stability faults. In
particular, DRFs and stability faults often result from variations in manufacturing
10 materials and processes. In the past, DRF and stability fault testing has been largely
functional in nature. Namely, a read/write algorithm is developed that functionally
exercises the SRAM. The read/write algorithm is then executed by a memory test
system external to the IC. From the results of the functional testing, an attempt is
made to deduce DRFs and stability faults for individual memory cells in the SRAM.

15 Recently, several test methodologies have been developed that directly test for
such failures instead of inferring the failures from functional tests. Moreover, some
of these test methodologies are well-suited to being implemented as a built-in self-test
(BIST), such that the cost and time associated with testing for DRF and stability faults
using an external memory test system are reduced or effectively eliminated. One such
20 methodology known as Weak Write Test Mode (WWTM) is disclosed by Banik et al.,
U.S. Pat. No. 5,559,745, incorporated herein by reference.

When testing an SRAM with WWTM, an attempt is made to overwrite a data
value stored in a memory cell using a “weak” write value or signal. The weak write
signal is only capable of overwriting the stored value in the memory cell if the
25 memory cell is unstable or defective. Thus, if the weak write test is successful, a
defect in the memory cell is indicated. An unsuccessful weak write test indicates a
healthy memory cell, at least with respect to stability and DRFs.

Weiss et al., U.S. Pat. No. 6,192,001 B1, incorporated herein by reference,
disclose a WWTM approach that integrates a weak write driver functionality into an

existing conventional column-associated write driver of the SRAM. According to Weiss et al., only two additional transistors are added to each conventional write driver in each set of columns as opposed to six transistors per column according to Banik et al. A set of columns is one or more columns depending on whether or not column multiplexing is employed in the SRAM. In particular, a first or weak write pull-down transistor is added that modifies a level of an output signal of the write driver when in WWTM and a second or bypass pull-down transistor is added that essentially bypasses the first transistor thereby facilitating a normal or strong write output signal to be produced by the write driver when not in WWTM.

Unfortunately, sizing of the weak write pull-down transistor of Weiss et al. presents certain practical difficulties in IC manufacturing. In particular, the weak write pull-down transistor must be big or strong enough to insure that the WWTM write driver output signal adequately exercises the memory cells of the SRAM, allowing for reliable detection of defective memory cells. Simultaneously, the weak write pull-down transistor must be small or weak enough such that the WWTM write driver output signal is not capable of overwriting data in healthy memory cells thereby producing false detection of defects.

In practice, the weak write pull-down transistor sizing is sensitive to variables and tolerances of a given manufacturing line and/or inadequacies of a design simulation to account for such variables and tolerances. Thus, many memory design and prototype iterations may be necessary to produce a properly sized weak write pull-down transistor. Moreover, each time the IC design is changed and/or the manufacturing process/line is changed or modified, the iterative design process typically must be repeated.

Accordingly, it would be advantageous to have a way to implement WWTM that was less sensitive to weak write pull-down transistor sizing. In addition, it would be advantageous if such implementations did not appreciably increase the number of transistors in the SRAM array or a number of traces in the SRAM IC used to access and activate WWTM. Such an implementation of WWTM would solve a long-standing need in the area of BIST for ICs that contain SRAM arrays.

SUMMARY OF THE INVENTION

The present invention provides a weak write test mode (WWTM) for static random access memory (SRAM). In particular, the present invention generates and employs a bias voltage having a selectable magnitude to bias a weak write pull-down transistor in a write driver of an SRAM.

In one aspect of the invention, a programmable weak write test mode (PWWTM) bias generator is provided. The PWWTM bias generator comprises means for generating an output signal that is a logic high level at an output of the PWWTM generator in a default mode when a WWTM is not asserted or not active.

10 The output signal is a bias voltage signal having a selectable or programmable magnitude at the output when the WWTM is asserted.

In some embodiments, the PWWTM bias generator comprises an array of transistors connected in parallel between a first supply voltage and an output of the PWWTM bias generator. Each of the array transistors of the array is individually selectable and by selecting may be individually activated. The PWWTM bias generator further comprises a pull-down transistor connected between the PWWTM bias generator output and a second supply voltage. The PWWTM bias generator further comprises a gate bias circuit connected between a mode select input and a gate of the pull-down transistor. The gate bias circuit biases the pull-down transistor.

15

20 Selecting and activating a particular one or more of the array transistors from the array selects a particular magnitude of the bias voltage at the PWWTM bias generator output.

The PWWTM bias generator generates an output signal or a bias voltage that is used to bias a gate of the weak write pull-down transistor of the SRAM array write driver when WWTM is asserted or active. A magnitude of the bias voltage controls an 'activated' strength of the weak write pull-down transistor that affects a WWTM output or drive level generated by the write driver. Thus, the PWWTM bias generator, through a set of selection inputs, controls the WWTM output level of the SRAM write driver during WWTM testing of the SRAM. Moreover, a default output level of the PWWTM bias generator, when the WWTM is not active, is a logic 'high' level or value, such that the weak write pull-down transistor is biased to an ON state.

25

30

Furthermore, a single PWWTM bias generator may be used to control a plurality of weak write pull-down transistors in a plurality of write drivers of the SRAM.

In another aspect of the invention, a weak write test mode (WWTM)-enabled SRAM system is provided. In yet another aspect of the invention, a method of driving a WWTM-equipped SRAM using a bias voltage output signal with a high logic level default mode is provided.

Certain embodiments of the present invention have other advantages in addition to and in lieu of the advantages described hereinabove. These and other features and advantages of the invention are detailed below with reference to the following drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The various features and advantages of the present invention may be more readily understood with reference to the following detailed description taken in conjunction with the accompanying drawings, where like reference numerals designate like structural elements, and in which:

Figure 1 illustrates a block diagram of a programmable weak write test mode (PWWTM) bias generator according to an embodiment of the present invention.

Figure 2 illustrates a block diagram of another embodiment of a programmable weak write test mode (PWWTM) bias generator according to the present invention.

Figure 3A illustrates a block diagram of an exemplary weak write test mode (WWTM)-enabled SRAM system according to an embodiment of the present invention.

Figure 3B illustrates a block diagram of an exemplary WWTM-configured write driver according to an embodiment of the present invention.

Figure 4 illustrates a block diagram of a programmable weak write test mode (PWWTM) generator circuit known in the art.

Figure 5 illustrates a flow chart of a method of driving a WWTM-equipped SRAM according to an embodiment of the present invention.

MODES FOR CARRYING OUT THE INVENTION

Figure 1 illustrates a block diagram of a programmable weak write test mode (PWWTM) bias generator 100 according to an embodiment of the present invention. The PWWTM bias generator 100 has two operational modes. A first operational mode corresponds to a weak write test mode (WWTM) of an associated static random access memory (SRAM) while a second mode corresponds to a normal read/write operational mode of the SRAM. In other words, when the WWTM is activated or asserted, the PWWTM bias generator 100 operates in the first mode or *WWTM*. Otherwise, the PWWTM bias generator 100 operates in a second mode or ‘not *WWTM*’. The second mode is also referred to herein as a ‘default’ mode. A mode select *MS* input of the PWWTM bias generator 100 controls a selection between the WWTM and the default mode.

When the operational mode is *WWTM*, the PWWTM bias generator 100 produces an output signal or a bias voltage V_{bias} having a programmable or selectable magnitude. The bias voltage V_{bias} is produced at an output 102 of the bias generator 100. The selectable magnitude of the bias voltage V_{bias} may take on values between a voltage value of a first supply voltage V_{DD} and a voltage value of a second supply voltage V_{SS} that is lower than the first supply voltage V_{DD} (i.e., $V_{SS} < V_{DD}$). Preferably, the second supply voltage V_{SS} is essentially zero volts (i.e., $V_{SS} \approx 0$ V) and is a ground potential or voltage of PWWTM bias generator 100. The selectable magnitude of the bias voltage V_{bias} in the WWTM is controlled by a set of selection inputs Sel_i of the PWWTM bias generator 100.

When the operational mode is the default mode or ‘not *WWTM*’, the output signal produced at the PWWTM bias generator output 102 defaults to a voltage level that represents a logic high or ‘1’ for the SRAM. Preferably, the default logic high of the output signal is approximately equal to the first supply voltage V_{DD} . Furthermore, the PWWTM bias generator 100 is capable of actively maintaining the default logic high level of the output signal while in the default mode when the output 102 is connected to a load.

The PWWTM bias generator 100 comprises an array 110 of p-type or p-channel metal oxide semiconductor (PMOS) transistors M0-M7. As illustrated in Figure 1,

the exemplary array 110 comprises eight PMOS transistors M0-M7 for discussion purposes only. Any number of PMOS transistors may be employed in the array 110 and still be within the scope of the present invention.

The transistors M0-M7 of the array 110 are connected between the first supply voltage V_{DD} and the output 102 of the PWWTM bias generator 100. In particular, as illustrated in the exemplary embodiment of Figure 1, each of the array transistors M0-M7 of the array 110 has a source connected to the first supply voltage V_{DD} and a drain connected to the output 102 of the PWWTM bias generator 100.

The set of selection inputs Sel_i are connected to all array transistors M0-M6 but a last array transistor M7 of the array 110. Specifically, a gate of each array transistors M0-M6 is connected to a different one of the selection inputs Sel_i of the set except for the last array transistor M7. In other words, a first selection input Sel_0 is connected to a gate of a first transistor M0 of the array 110. A second selection input Sel_1 is connected to a gate of a second transistor M1 of the array 110, and so on. A gate of the last array transistor M7 is connected to the mode select MS input of the PWWTM bias generator 100.

The set of selection inputs Sel_i control activation of the array transistors M0-M6. In particular, the individual selection inputs Sel_i control which of the array transistors M0-M6 are active, ‘turned ON’ or placed in an ON state, and which are inactive, ‘turned OFF’ or placed in an OFF state. Similarly, the mode select MS input controls whether or not the eighth or last array transistor M7 is turned ON. When turned ON, a metal oxide semiconductor (MOS) transistor approximates a resistor and a current I_{ds} may flow through the MOS transistor. When turned OFF, the MOS transistor approximates an open circuit. Thus, when activated by asserting one or more of the selection inputs Sel_i of the set and/or the mode select MS input, the array 110 conducts current from the first supply voltage V_{DD} and acts to ‘pull-up’ the bias voltage V_{bias} toward a level of the first supply voltage V_{DD} . For example, asserting the second selection input Sel_1 by applying a logic low ‘0’ (i.e., $Sel_1 \approx 0$ V) turns ON the second transistor M1 of the array 110. The second transistor M1 then pulls-up the bias voltage V_{bias} . Similarly, the eighth transistor M7 acts to pull up the bias voltage V_{bias} .

when *WWTM* is not asserted by way of the mode select *MS* input (i.e., *MS* = '0'). As such, each of the transistors *M0-M7* of the array 110 is a 'pull-up' transistor.

In some embodiments of the PWWTM bias generator 100, each of the array transistors *M_i* is a different size from one another. For example, the first array transistor *M0* may be smaller than the second array transistor *M1*. Likewise, the second array transistor *M1* may be smaller than a third transistor *M2* of the array 110, and so on. Preferably, the eighth array transistor *M7* (or the last array transistor, for example) is larger than the other transistors *M0-M6* of the array 110.

As used herein, transistor size generally relates to an effective resistance of an active or turned ON transistor. In particular, for a given metal oxide semiconductor (MOS) manufacturing process, size is essentially an inverse function of a ratio between a gate width or transistor width and a gate length or transistor length. Thus, for a given length, a greater width produces a lower effective resistance when the MOS transistor is turned ON.

Related to the transistor size is a transistor strength. Transistor strength is typically associated with a current sourcing or sinking capacity of the transistor. For example, a stronger transistor can source more current than a weaker transistor. However, as used herein, transistor strength and transistor size are used essentially interchangeably. Specifically, a larger transistor is a stronger transistor. However, while transistor strength is related to transistor size, a bias voltage applied to a gate of the transistor can also affect transistor strength. In particular, a bias voltage having a level between a level that turns ON the transistor and a level that turns OFF the transistor may be employed to modulate the transistor strength. One skilled in the art is familiar with transistor size and transistor strength and the relationship between size/strength and the ON state resistance of the transistor. In particular, one skilled in the art may readily determine appropriate sizes/strengths of any and all of the MOS transistors used in the PWWTM bias generator 100 without undue experimentation.

In other exemplary embodiments, each of the PMOS transistors *M_i* of the array 110 are essentially the same size as one another. In such embodiments, the mode select *MS* input may be combined with the selection inputs *Sel_i*, such that when *WWTM* is asserted on the mode select *MS* input, the selection inputs *Sel_i* may be

individually and independently asserted. Alternatively, when *WWTM* is not asserted on the mode select *MS* input, all of the transistors M0-M7 of the array 110 preferably are turned ON to cooperatively pull up the bias voltage V_{bias} . Thus, in the example having array transistors M0-M7 of the same size, no particular or single array transistor functions as the pull-up transistor when in the default mode. Instead, all of the transistors M0-M7 of the array 110 act together to pull-up the bias voltage V_{bias} to the logic high '1' level.

Moreover in some embodiments, one or more of the transistors M_i of the array 110 may actually represent a plurality of PMOS transistors connected in one or more of a series and a parallel configuration. For example, the first PMOS transistor M0 may comprises a pair of PMOS transistors (not illustrated) connected in series and acting as a single transistor with respect to the first selection input Sel_0 .

The PWWTM bias generator 100 further comprises an n-type or n-channel metal oxide semiconductor (NMOS) transistor M8. The transistor M8 is preferably a weak transistor. The transistor M8 is connected between the output 102 of the PWWTM bias generator 100 and the second supply voltage V_{SS} . In particular, a drain of the transistor M8 is connected to the output 102 and a source of the transistor M8 is connected to the second supply voltage V_{SS} .

A gate voltage V_g generally greater than zero volts applied to a gate of the transistor M8 activates or turns ON the transistor M8. In particular, a high level or logic "1" applied to the gate turns ON the transistor M8. When turned ON, the transistor M8 conducts a current I_{ds} from the output 102 to the second supply voltage V_{SS} or ground. Furthermore, the gate voltage V_g equal to approximately zero volts ($V_g = 0$ V) turns OFF the transistor M8. The effect of turning ON the transistor M8 is to 'pull-down' the bias voltage V_{bias} toward the second supply voltage V_{SS} or ground potential. Thus, the transistor M8 is a pull-down transistor, preferably a weak pull-down transistor, when active or turned ON.

The gate voltage V_g is related to the operational mode asserted using the mode select *MS* input. In particular, when *WWTM* is asserted on the mode select *MS* input, a positive (non-zero) gate voltage V_g is preferably applied to the transistor M8 gate. Likewise, when *WWTM* is not asserted on the mode select *MS* input, a logic low '0' is

preferably applied to the transistor M8 gate. Thus for example, the gate of the pull-down transistor M8 may be directly connected to and driven by the mode select *MS* input. Preferably however, the PWWTM bias generator 100 further comprises a gate bias circuit 120 connected between the mode select *MS* input and the gate of the pull-down transistor M8.

As illustrated in the exemplary embodiment of Figure 1, the gate bias circuit 120 of the PWWTM bias generator 100 comprises an NMOS transistor M9 connected between the NMOS transistor M8 gate and the second supply voltage V_{SS} that functions as a pull-down transistor. The gate bias circuit 120 further comprises a PMOS transistor M10 and an NMOS transistor M11 connected between the output 102 and the gate of the pull-down transistor M8. Together, the transistors M10 and M11 operate as a conventional transmission gate. The gate bias circuit 120 further comprises an inverter 122, an output of which is connected to a gate of the PMOS transistor M10 and a gate of the NMOS transistor M9. A gate of the NMOS transistor M11 and an input of the inverter 122 are connected to the mode select *MS* input of the PWWTM bias generator 100.

When *WWTM* is asserted (i.e., *MS* = '1'), the inverter 122 produces a logic '0' output signal and the transistor M11 is turned ON. The logic '0' signal turns OFF the transistor M9 and turns ON the transistor M10. As noted hereinabove, the combination of the transistors M11 and M10 is essentially a transmission gate known in the art. Thus, when both transistors M10, M11 are turned ON, the gate voltage V_g on the gate of the transistor M8 becomes approximately equal to the bias voltage V_{bias} . With the bias voltage V_{bias} essentially applied to the gate of the transistor M8, the transistor M8 is turned ON.

Also mentioned hereinabove, when *WWTM* is asserted (i.e., *MS* = '1'), the array transistor M7 is turned OFF. Assuming at least one of the array transistors M0-M6 are selected (i.e., one of Sel_i = '0' for $i = 0, \dots, 6$), current flows from the supply voltage V_{DD} through the array 110 and to the output 102. Simultaneously, current flows from the output 102 through the pull-down transistor M8 to the supply voltage or ground V_{SS} . The combination of the pull-up action of the array 110 and the pull-down action of the transistor M8 establish the selectable magnitude of the bias voltage

V_{bias} . In essence, the array 110 in combination with the activated pull-down transistor M8 approximates a voltage divider circuit. Moreover, a division factor of the divider circuit is set by a ratio between an effective resistance of the activated pull-down transistor M8 and an effective resistance of selected one or more of the array transistors M0-M6 of the array 110. In other words, a ratio between a size of the weak pull-down transistor M8 and an effective size of the activated transistors M0-M6 of the array 110 establishes the magnitude of the bias voltage V_{bias} . The effective size of the active array transistors M0-M6 is a sum of the sizes of one or more of the selected array transistors M0-M6. As described hereinabove, an array transistor M0-M6 is selected by applying a logic '0' to one or more of the corresponding selection inputs Sel_i of the PWWTM bias generator 100. Thus, by selecting an appropriate one or more of the array transistors M0-M6, the division factor is selected, and by selecting the division factor, the magnitude of the output signal or the bias voltage V_{bias} is selected.

For example, if each of the array transistors M0-M6 has a different unique size, then individually selecting one of the array transistors M0-M6 enables any one of seven different magnitudes of the bias voltage V_{bias} to be selected. Additional bias voltage V_{bias} magnitudes may be selected by selecting combinations of the array transistors M0-M6. Changing a size difference between a smallest transistor in the array 110 and a largest transistor in the array 110 may adjust an extent of a range of selectable magnitudes. A median bias voltage V_{bias} magnitude may be adjusted by adjusting a relative size of the pull-down transistor M8 with respect to a median size of the transistors M0-M6 of the array 110. One skilled in the art will readily recognize that the relative size of the transistors M0-M6 and M8 may be adjusted by adjusting one or both of an actual size of the pull-down transistor M8 and an actual median size of the array transistors M0-M6. Moreover, one skilled in the art may readily determine the relative and actual sizes of the array transistors M0-M6 and the pull-down transistor M8 to produce any desired set of selectable bias voltage V_{bias} magnitudes without undue experimentation.

When $WWTM$ is not asserted (i.e., $MS = '0'$), the PWWTM bias generator 100 is placed in the default mode. In the default mode, the inverter 122 produces a logic '1' output signal and the transistor M11 is turned OFF. The logic '1' output signal of the

inverter 122 turns ON the transistor M9 and turns OFF the transistor M10. With both transistors M10 and M11 turned OFF, the transmission gate formed by transistors M10 and M11 is turned OFF. The transistor M9 turned ON and the transmission gate turned OFF causes the gate voltage V_g on the gate of the pull-down transistor M8 to
 5 be pulled down to approximately the second supply voltage V_{SS} or to approximately ground potential. As a result, the pull-down transistor M8 is turned OFF.

Furthermore, since $WWTM$ is not asserted, a logic '0' is applied to the gate of the eighth or last transistor M7 of the array 110 and the eighth or last transistor M7 is turned ON. With the eighth/last transistor M7 turned ON and the pull-down transistor
 10 M8 turned OFF, current flowing through the activated eighth/last transistor M7 pulls up the bias voltage V_{bias} to approximately the first supply voltage V_{DD} . Thus advantageously, the produced output signal of the PWWTM bias generator 100 illustrated in Figure 1 defaults to a logic high '1' when $WWTM$ is not asserted.

Figure 2 illustrates another embodiment of a programmable weak write test mode (PWWTM) bias generator 100' according to the present invention. The
 15 PWWTM bias generator 100' is similar to the PWWTM bias generator 100. In particular, the PWWTM bias generator 100' comprises the array 110 and the pull-down transistor M8. Furthermore, the PWWTM bias generator 100' produces an output signal or a bias voltage V_{bias} when $WWTM$ is asserted at the mode select MS input and the output signal defaults to a logic high '1' voltage level when $WWTM$ is
 20 not asserted as the mode select MS input. The PWWTM bias generator 100' differs from the previously described PWWTM bias generator 100 essentially in that another, somewhat simpler, gate bias circuit 120' is employed in place of the gate bias circuit 120 described hereinabove.

25 The gate bias circuit 120' comprises the inverter 122 and the pull-down transistor M9 connected as described hereinabove with respect to the gate bias circuit 120. The simpler gate bias circuit 120' further comprises a pull-up transistor M12 connected between the supply voltage V_{DD} and the gate of the pull-down transistor M8. A gate of the pull-up transistor M12 is connected to the output of the inverter
 30 122. Omitted from the gate bias circuit 120' are the transistor M10 and the transistor M11 that formed the transmission gate of the gate bias circuit 120.

The gate bias circuit 120' operates to drive the pull-down transistor M8 in a manner that is essentially similar to that previously described hereinabove. In particular, when *WWTM* is asserted, the inverter 122 produces a logic low '0' output signal. The logic low '0' output signal turns OFF the pull-down transistor M9 and turns ON the pull-up transistor M12. The gate voltage V_g is pulled up to the supply voltage V_{DD} and the transistor M8 is turned ON. Alternatively, when *WWTM* is not asserted, the inverter 122 produces a logic high '1' output signal. The logic high '1' output signal turns ON the pull-down transistor M9 and turns OFF the pull-up transistor M12. The gate voltage V_g is pulled down to the second supply voltage V_{SS} or ground and the transistor M8 is turned OFF.

One skilled in the art may readily devise other variations of the gate bias circuit all of which are within the scope of the present invention. For example, a gate bias circuit may be implemented as a single non-inverting driver (not illustrated) connected between the mode select *MS* input and the gate of the pull-down transistor M8. In yet another embodiment as noted hereinabove, a gate bias circuit may be essentially omitted entirely by connecting the mode select *MS* input directly to the gate of the pull-down transistor M8. Other variations of the PWWTM bias generator 100, 100' within the scope of the present invention include, but are not limited to, using an array of individually selectable transistors (not illustrated) in place of or in addition to the pull-down transistor M8.

According to the present invention, the PWWTM bias generator 100, 100' provides the output signal or the bias voltage V_{bias} to a static random access memory (SRAM) having a weak write test mode configuration. Figure 3A illustrates a block diagram of an exemplary weak write test mode (WWTM)-enabled SRAM system 200 according to an embodiment of the present invention. The WWTM-enabled SRAM 200 comprises a WWTM-configured SRAM array 201 and the PWWTM bias generator 100, 100'. The WWTM-configured SRAM array 201 comprises a plurality of memory cells 210 arranged in columns and a plurality of write drivers 220, each write driver 220 driving one or more of the columns. The SRAM array 201 has a *WRITE* input, an inverse mode select \overline{MS} input, a set of *WORD* inputs, and a set of *DATA* inputs. Both the *WRITE* input and the inverse mode select \overline{MS} input are

connected to each write driver 220 of the plurality at respective inputs thereof. Each write driver 220 connects to a different *DATA* input of the set of *DATA* inputs. The output 102 of the PWWTM bias generator 100, 100' connects to a corresponding analog weak write test mode (AWWTM) input of each of the write drivers 220.

5 Each write driver 220 connects to the memory cells 210 in the associated column through a *BIT* line and an inverse \overline{BIT} line. Each memory cell 210 in the column connects to a different *WORD* input of the set. The *WORD* inputs are sometimes referred to as 'row selects' given the association between the *WORD* inputs and rows of memory cells 210 in the SRAM array 201. The inverse mode
10 select \overline{MS} input controls whether or not the write driver 220 operates in weak write test mode (WWTM) when writing data to a selected memory cell 210 in the column.

To write data to an individual memory cell 210, a corresponding *WORD* input is asserted (e.g., *WORD* = '1'). Assertion of the *WORD* input enables a connection within the memory cell 210 between the memory cell 210 and the *BIT* and \overline{BIT} lines
15 of the column. The write driver 220 then drives the *BIT* and \overline{BIT} lines with the data from the connected *DATA* input.

For example, when the WWTM is not asserted (i.e., *MS* = '0', or \overline{MS} = '1'), the write driver 220 performs a strong write to the selected memory cell 210. The term 'strong write' is a term of art that is relative to another term of art 'weak write', which
20 is described further below. Thus, if the data on the *DATA* input is a '1', the write driver 220 produces a logic high '1' on the *BIT* line and a logic low '0' on the inverse \overline{BIT} line. Conversely, if the data on the *DATA* input is a '0', the write driver 220 produces a logic low '0' on the *BIT* line and a logic high '1' on the inverse \overline{BIT} line. When presented with the strong write, the selected memory cell 210 latches the data
25 encoded by the *BIT* and \overline{BIT} lines, overwriting a previous state of the memory cell 210.

In another example, when the WWTM is asserted (i.e., *MS* = '1', or \overline{MS} = '0'), the write driver 220 performs a weak write to the selected memory cell 210, as opposed to the 'strong write' mentioned above. As described in Banik et al., a weak
30 write consists of writing to a memory cell 210 using an abnormal signal level or

value. Typically, the abnormal signal level is a signal level that deviates from or falls short of a normal signal level. Thus, if the data on the *DATA* input is a '1', the write driver 220 produces a voltage level on the *BIT* line somewhat below a normal logic '1' voltage level. At the same time, the write driver 220 produces a voltage level on the inverse \overline{BIT} line that is somewhat above a normal logic '0'. According to the WWTM methodology, if the abnormal signal levels produced by the write driver 220 are capable of causing the selected memory cell 210 to change state (e.g., overwrite a '0' with a '1'), then the memory cell 210 is considered defective.

Figure 3B illustrates a block diagram of an exemplary WWTM-configured write driver 220 according to an embodiment of the present invention. The WWTM-configured write driver 220 illustrated in Figure 3B is based on the integrated WWTM SRAM disclosed by Weiss et al. In particular, the write driver 220 comprises PMOS transistors M21 and M24, NMOS transistor M22, M23, M25 and M26, and an inverter 222. The transistors M21 and M22 are connected to form a first conventional inverter/driver 223. In particular, drains of the transistors M21 and M22 are connected together to form an output of the inverter/driver 223 while gates of the transistors M21 and M22 are connected together to form an input of the inverter/driver 223. The output of the inverter/driver 223 is connected through a pass transistor M25 to the *BIT* line. A gate of the pass transistor M25 is connected to and enabled by the *WRITE* input of the SRAM array 201. The input of the inverter/driver 223 is connected to an output of the inverter 222. A source of the transistor M21 in the inverter/driver 223 is connected to the supply voltage V_{DD} .

In a similar manner to the first inverter/driver 223, the transistors M24 and M23 are connected to form a second conventional inverter/driver 224. An output of the second inverter/driver 224 is connected through a pass transistor M26 to the inverse \overline{BIT} line. A gate of the pass transistor M26 is connected to and enabled by the *WRITE* input of the SRAM array 201. Both an input of the inverter/driver 224 and an input of the inverter 222 are connected to a respective *DATA* input associated with the write driver 220. A source of the transistor M24 in the inverter/driver 224 is connected to the supply voltage V_{DD} .

The write driver 220 further comprises a bypass NMOS transistor M27 and a weak write pull-down NMOS transistor M28. A source of the transistor M22 of the first inverter/driver 223 and a source of the transistor M23 of the second inverter/driver 224 are connected together and connected to a source of the bypass transistor M27 and a source of the weak write pull-down transistor M28. A drain of each of the bypass transistor M27 and the weak write pull-down transistor M28 are connected to the second supply voltage V_{SS} or ground. A gate of the bypass transistor M27 is connected to the inverse mode select \overline{MS} input of the SRAM array 201. A gate of the weak write pull-down transistor M28 is connected to the output 102 of the PWWTM bias generator 100, 100' and receives output signal from the PWWTM bias generator 100, 100' output 102.

When operating in normal write mode (i.e., the WWTM is not asserted and $MS = '0'$, $\overline{MS} = '1'$), both of the transistors M27 and M28 are turned ON. The bypass transistor M27 is turned ON by virtue of the application of the inverse mode select \overline{MS} input. The weak write pull-down transistor M28 is turned ON by virtue of the default logic high '1' level of the output signal produced by the PWWTM bias generator 100, 100'. As a result, the drains of the transistors M22 and M23 are pulled down to essentially the second supply voltage V_{SS} or ground.

Alternatively, when operating in the WWTM (i.e., $WWTM$ is asserted and $MS = '1'$, $\overline{MS} = '0'$), the bypass transistor M27 is turned OFF. In addition, the bias voltage V_{bias} output signal produced by the PWWTM bias generator 100, 100' is applied to the gate of the weak write pull-down transistor M28. As a result of the weak write pull-down action of the transistor M28, a generally non-zero bias voltage will be present at the sources of the transistors M22 and M23. The presence of the non-zero bias voltage on the transistor M22, M23 sources causes the voltages produced by the inverter/drivers 223, 224 to fall short of normal logic voltage levels. Thus, a 'weak' logic signal is presented to the selected memory cell 210 by way of the pass transistors M25, M26.

An actual level of the non-zero bias voltage at the sources of the transistors M22 and M23 will depend on the size of the weak write pull-down transistor M28 and the selected magnitude of the bias voltage V_{bias} . In particular, by selecting a different one

of the selectable magnitudes using the PWWTM bias generator 100, 100' array 110, as described above, an actual level of the non-zero bias voltage V_{bias} may be increased or decreased. The operation or effective pull-down strength of the weak write pull-down transistor M28 is modulated by the selectable magnitude of the bias voltage V_{bias} produced by the PWWTM bias generator 100, 100' according to the present invention.

Advantageously, manufacturing variations in a typical strength of the weak write pull-down transistor M28 may be accounted for by selecting a particular one of the available selectable magnitudes of the bias voltage V_{bias} . Such an ability to account for manufacturing variations in the strength of the transistor M28 may increase yields during manufacturing and decrease a number of design iterations needed to produce acceptable yields. In addition, the logic high '1' output signal produced by the PWWTM bias generator 100, 100' according to the present invention turns ON the weak write pull-down transistor M28 when the WWTM is not asserted. By turning ON the weak write pull-down transistor M28 in parallel with the bypass transistor M27 also being turned ON, according to the present invention, a write margin of the memory cell 210 may be improved. Advantageously, the improved write margin may also increase yields during manufacturing.

Figure 4 illustrates a programmable weak write test mode (PWWTM) generator circuit 300 known in the art. The PWWTM generator circuit 300 has a set of selection inputs Sel_1 - Sel_7 , a mode select MS input, an inverse mode select \overline{MS} input, and an output 302. When the WWTM is asserted on the mode select MS input (i.e., $MS = '1'$ and $\overline{MS} = '0'$), the PWWTM generator circuit 300 produces at the output 302 an output signal or a bias voltage V_{bias} that has a selectable magnitude. The selectable magnitude is controlled by the selection inputs Sel_1 - Sel_7 . Note that in general for normal operation of the PWWTM generator circuit 300, Sel_7 is set equal to mode select MS (i.e., $Sel_7 = MS$). When the WWTM is not asserted (i.e., $MS = '0'$, $Sel_7 = '0'$, and $\overline{MS} = '1'$), the PWWTM generator circuit 300 produces an output signal representing a logic low '0' level at the output 302. In other words, the PWWTM generator circuit 300 defaults to a logic low '0' output signal when the WWTM is not asserted.

The conventional PWWTM generator circuit 300 comprises an array 310 of PMOS transistors M30-M37. The source of each of the transistors M30-M37 is connected to the supply voltage V_{DD} . A gate of each of the transistors M30-M37 is connected to a different selection input of the set Sel_0 - Sel_7 . The transistor M30 is a
 5 smallest or weakest transistor of the array 310 having a relatively highest ON state resistance, while the transistor M37 is a largest or strongest transistor of the array 310 having a relatively lowest ON state resistance.

The conventional PWWTM generator circuit 300 further comprises a PMOS transistor M38 and an NMOS transistor M39. A source of the transistor M38 is
 10 connected to drains of each of the transistors M30-M37 of the array 310. A gate of the transistor M38 and a gate of the transistor M39 are connected to the inverse mode select \overline{MS} input of the generator circuit 300. A drain of the transistor M38 and a drain of the transistor M39 are connected to the output 302 of the generator circuit 300. A source of the transistor M39 is connected to the supply voltage V_{SS} .

15 The conventional PWWTM generator circuit 300 further comprises a weak pull-down NMOS transistor M40. The weak pull-down transistor M40 has a drain connected to the output 302 and a source connected to the supply voltage V_{SS} or ground. A gate of the weak pull-down transistor M40 is connected to an output of a gate bias circuit 320. The gate bias circuit 320 is essentially similar to the gate bias
 20 circuit 120 described hereinabove. In particular, the gate bias circuit 320 comprises an inverter 322, a pull-down NMOS transistor M41, a PMOS transistor M42, and an NMOS transistor M43. A drain of the transistor M41 is connected to the gate of the weak pull-down transistor M40 while a source of the transistor M41 is connected to the supply voltage V_{SS} . A source of the transistor M42 and a drain of the transistor
 25 M43 are connected together and connected to the output 302. A drain of the transistor M42 and a source of the transistor M43 are connected together and connected to the gate of the transistor M40. Together, transistors M42 and M43 form a transmission gate similar to transmission gate described with respect to the gate bias circuit 120 hereinabove. An output of the inverter 322 is connected to a gate of the pull-down
 30 transistor M41 and a gate of the transistor M42. An input of the inverter 322 and a

gate of the transistor M43 are connected to an eighth selection input Sel_7 . As noted hereinabove, the selection input Sel_7 functions as the mode select MS input.

When the WWTM is asserted (i.e., $MS = '1'$ and $\overline{MS} = '0'$), the transistor M38 is turned ON and transistor M39 is turned OFF. The gate bias circuit 320 applies a gate voltage V_g approximately equal to the bias voltage V_{bias} to the gate of the weak pull-down transistor M40 that turns ON the transistor M40. The selectable magnitude of the bias voltage V_{bias} output signal is controlled by selecting and turning ON one of the transistors M30-M37 using the selection inputs Sel_0 - Sel_7 . A resistive divider formed by an effective state resistance of the selected transistor M30-M37 of the array 310 in series with the ON state resistance of the transistor M39 and the ON state resistance of the weak pull-down transistor M40 determines the actual magnitude of the bias voltage V_{bias} in a manner similar to that described hereinabove with respect to the bias generator 100, 100', but without a need for the transistor M39.

When the WWTM is not asserted (i.e., $MS = '0'$ and $\overline{MS} = '1'$), the transistor M38 is turned OFF and the transistor M39 is turned ON. In addition, the gate bias circuit 320 insures that the weak pull-down transistor M40 is turned OFF. Since transistor M38 is OFF, no current can flow from the supply voltage V_{DD} to the output 302. Furthermore, since transistor M39 is turned ON, a logic low '0' output signal approximately equal to the supply voltage V_{SS} or ground is produced at the output 302.

In contrast to the PWWTM bias generator 100, 100' according to the present invention, the conventional PWWTM generator circuit 300 defaults to a logic low '0' output signal when WWTM is not asserted. In the SRAM system 200 illustrated in Figure 3A, the conventional PWWTM generator circuit 300 in place of the PWWTM bias generator 100, 100' of the present invention will affect the SRAM array 201 in a nontrivial way. For example, when the conventional PWWTM generator circuit 300 defaults to the logic low '0' output signal, the weak write pull-down transistor M28 of the SRAM array write driver 220 is turned OFF by the PWWTM generator circuit 300. Thus, employing the PWWTM generator circuit 300 does not improve the write margin of the memory cell 210.

The conventional PWWTM generator circuit 300 also generally uses larger transistors than those used to implement the PWWTM bias generator 100, 100' according to the present invention. In particular, the presence of the series resistance of the transistor M38 in the conventional circuit 300 results in a need to increase sizes of the transistors M30-M37 in the array 310 relative to those in the array 110 of the present invention to achieve equivalent results with respect to the selectable magnitudes of the produced bias voltage V_{bias} . For example, if implementations of the bias generator 100 of the invention and the conventional generator circuit 300 having equivalent selectable magnitudes of the bias voltage V_{bias} output signal are compared, a total length of array transistors M0-M7 is approximately one half a total length of the array transistors M30-M37.

Table 1 presents simulation results that compare relative transistor sizes (i.e., widths) for the array transistors M0-M7 and the array transistors M30-M37 of the PWWTM bias generator 100 and the conventional PWWTM generator circuit 300, respectively. Table 1 also includes a target failing resistance R associated with the weak write pull-down transistor M28 of the SRAM array write driver 220 to produce a failure of the memory cell 210 during *WWTM* testing and further includes a selected magnitude of the bias voltage V_{bias} in volts produced by the bias generator 100 and conventional generator circuit 300 during *WWTM* testing.

Table 1

	Target Failing R	V_{bias} (V)	Size (M0-M7)	Size (M30-M37)
0	700K	0.562	0.54	0.58
1	360K	0.589	0.64	0.70
2	160K	0.651	0.91	1.02
3	90K	0.717	1.26	1.49
4	60K	0.778	1.66	2.11
5	40K	0.856	2.31	3.49
6	30K	0.927	3.12	6.23
7	14K	1.246	3.12	6.23

The transistor sizes (widths) presented in Table 1 are in microns and assume a gate length of 0.09 μm for the listed transistors. The simulation employed a 2.0/0.1 μm (width/length) for the transistor M28 and a 0.88/0.12 μm (width/length) for the

transistor M40. According to the simulation results, a total width of the transistors M0-M7 is 13.56 μm , as opposed a total width of 21.85 μm for the transistors M30-M37. Thus, the PWWTM bias generator 100, 100' according to the present invention may be smaller and consume less IC real estate than the PWWTM generator circuit
 5 300 known in the art.

Figure 5 illustrates a flow chart of a method 400 of driving a weak write test mode (WWTM)-equipped static random access memory (SRAM) according to an embodiment of the present invention. The method 400 of driving comprises generating 410 a bias voltage having a selectable magnitude and applying 420 the
 10 generated bias voltage to a gate of a weak write pull-down transistor of a write driver while conducting a WWTM test of the SRAM. The weak write pull-down transistor is preferably a transistor between a ground connection of one or more inverters of the write driver and a circuit ground V_{SS} of the SRAM. The selectable magnitude bias voltage modulates an effective 'ON' state resistance of the weak write pull-down
 15 transistor. By modulating the ON state resistance, a threshold of a detected memory cell failure may be adjusted. In particular, the threshold may be adjusted by selecting an appropriate magnitude from among the selectable magnitudes. The capability to adjust the threshold may be used to account for manufacturing related variations in the ON state resistance of the weak write pull-down transistor.

20 The method 400 further comprises generating 430 a logic high '1' output signal and applying 440 the logic high '1' signal to the gate of the weak write pull-down transistor while in a default mode or i.e., not conducting a WWTM test of the SRAM. The logic high signal '1' has a voltage that is sufficient to turn ON the weak write pull-up transistor. Preferably, the logic high signal '1' is essentially equal to a supply
 25 voltage V_{DD} . The application 440 of the logic high '1' signal insures that the weak write pull-down transistor is turned ON when the SRAM is operating in a normal mode (i.e., not conducting a WWTM test). Advantageously, the application 440 of the logic high '1' signal may improve a write margin of memory cells in the SRAM.

30 One or more of the following features and/or advantages may be realized by the present invention. The selectable magnitude or level of the output signal bias voltage may be used to account or compensate for process variations in the weak write pull-

down transistor strength. In particular, the selectable magnitude bias voltage facilitates SRAM manufacturing by reducing a need for iterative design adjustments of the weak write pull-down transistor size. Thus, according to the present invention, sensitivity to weak write pull-down transistor sizing of the SRAM undergoing weak write testing is reduced. Furthermore, the default high-level output of the PWWTM bias generator 100, 100' according to the present invention may improve a write margin of the SRAM by biasing the weak write pull-down transistor to the ON state when WWTM is not activated. Moreover, since one PWWTM bias generator 100, 100' may be used to bias any number of weak write pull-down transistors in the SRAM, a cost in terms of circuit area for using the PWWTM bias generator 100, 100' is very small compared to a total circuit area of the SRAM.

Thus, there have been described a PWWTM bias generator 100, 100' and a WWTM-enabled SRAM system 200. In addition, a method 400 of driving a WWTM equipped SRAM is disclosed. It should be understood that the above-described embodiments are merely illustrative of some of the many specific embodiments that represent the principles of the present invention. Clearly, those skilled in the art can readily devise numerous other arrangements without departing from the scope of the present invention as defined by the following claims.